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Spectral-Line Intensities and gf-Values in the First Spectrum of Copper

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Relative intensities are reported for 180 lines of Cu I between 2600 A and 7200 A, observed in a 10-ampere copper arc. Oscillator strengths, normalized as closely as possible to the absolute scale, are derived from the observations.

1. Introduction

The line intensities reported in the NBS Tables of Spectral-Line Intensities [1] [1] were observed in a 10-amp arc in air between copper electrodes containing one atom of an added element for every 1,000 atoms of copper. In order to reduce the original observations to a true scale of relative intensities, numerous lines in the first spectrum of copper were selected to serve as reference standards of intensity. The relative power radiated by these lines was measured by comparing the copper spectrum with the spectra from an incandescent ribbon-filament lamp operated at a known temperature and from a calibrated hydrogen-lamp continuum. The measurements were made by the standard methods of heterochromatic photographic photometry and are described in detail in the NBS Tables [1] and elsewhere by Meggers, Corliss, and Scribner [2].

From 2 to 24 determinations were made on each of 207 lines of Cu I between 2600 and 8100 A, with an average of about 9 determinations per line. A section of a typical plate is shown in figure 1.

The spectrum of copper consists of sharp lines and diffuse lines. In this investigation the spectrograph slit was adjusted to a sufficient width to form flat-topped images of the sharp lines. Intensities measured in the plateau of these images are proportional to the total intensities integrated over the widths of the lines. Measurements were not made on the diffuse lines.

[1] Figures in brackets indicate the literature references at the end of this paper

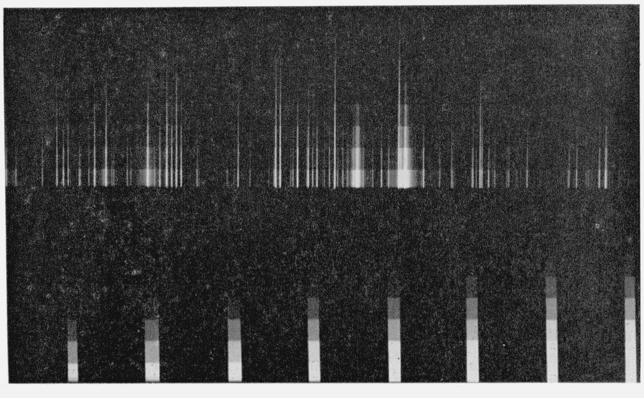

FIGURE 1. *Typical plate for the measurement of spectral-line intensities in copper.*

Spectral range 3400 to 3850 A. Above, arc spectrum of copper through rotating stepped sector. Below, spectrum of standard ribbon-filament lamp through a mask at intervals of 50 A and with the same sector.

2. Self-absorption in Strong Lines

The particle density of neutral copper atoms in the positive column of our 10-amp copper arc is about 10^{15} cm^{-3} [3]. At this density the gas is optically thick at the wavelengths of the strong lines and they are affected by self-absorption, as shown in figure 2. In this figure, I is the intensity of a strong copper line measured in the copper arc and I_0 is the intensity of the same line measured on the same intensity scale in a similar arc between silver electrodes to which one atom of copper was added for every 1000 atoms of silver. The copper lines in silver were measured relative to the intensities of lines of other elements also added to the silver and previously measured relative to copper lines in a copper arc. By this procedure we would expect copper lines that are free of absorption in the copper arc to be 1,000 times as strong in the copper arc as in the silver arc.

Inspection of figure 2 discloses that the ratio I/I_0 approaches 1,000 as I_0 diminishes. I_0 is actually the

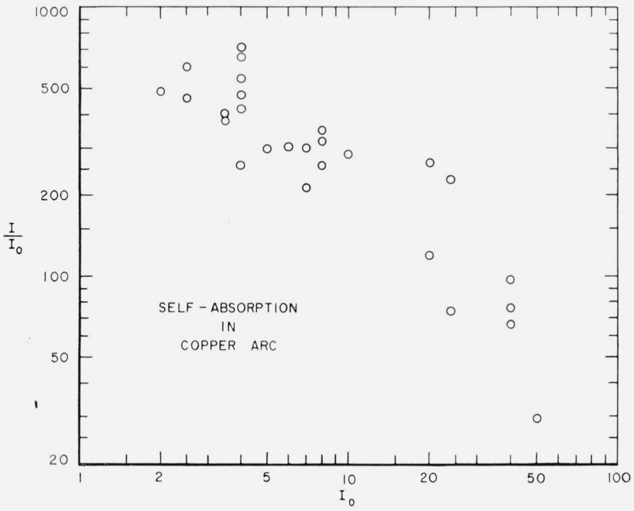

FIGURE 2. *Self-absorption in a 10-amp copper arc, showing how the amount of self-absorption diminishes for fainter lines.*

The points represent 27 lines over the wavelength range from 2824 to 8092 A, and having upper energy levels between 30 and 72 kK.

scale of intensity of the NBS Tables. This scale has a lower limit of the order of one. We may say then that copper lines too faint to appear in the NBS Tables will not be perceptibly affected by self-absorption in the 10-amp copper arc in air. Of the 207 lines measured in the copper arc, 27 appear in the NBS Tables. The remaining 180 lines will be unaffected by self-absorption and it is for these lines only that we will derive oscillator strengths. Figure 2 is plotted for the 27 strong reference standard lines without regard to wavelength or excitation potential.

3. Derivation of Oscillator Strengths From Intensities

The following formula has been developed [4, 5] for deriving absolute *gf*-values from the intensities in the NBS Tables of Spectral-Line Intensities:

$$gf = C(u/Np)I\lambda^3 e^{E/kT}$$

where u is the partition function at 5100 °K for the atom or ion under consideration, N is the percent of the element in the neutral or ionized state, p is the persistence of the atom in the arc relative to copper, I is the intensity of the line on the scale used in the NBS Tables, E is the value of the upper energy level, k is Boltzmann's constant, and T is the effective temperature of the arc. The effective temperature of our copper arc has been determined to be 5100 °K [6]. For Cu I, u is 2.4, N is 93 percent, and p is of course unity. N is calculated from Saha's ionization equation in which the electron density is taken to be 2.4×10^{14} cm^{-3} [3].

C is a normalization function, determined from absolute *gf*-values for 21 different elements in the NBS Tables, that adjusts the scale to an absolute basis. In the case of our copper lines, we must divide this C (shown in figure 3) by 1,000 since the particle density of copper atoms is 1,000 times the density of the atoms for which the formula was developed, and the intensity scale is increased correspondingly. The drooping characteristic of this function at large values of E is caused by preferential excitation of lines from high levels close to the electrodes of the arc. Over 90 percent of our copper lines fall on this nonconstant portion of the function.

The results are given in table 1. In the columns are listed in the following order the intensity on the scale of the NBS Intensity Tables, the wavelength to two decimal places and the two energy levels to the nearest kayser taken from Shenstone [7], $gA \times 10^{-8}$ sec^{-1}, gf, and log gf. The transition probability, g_nA, is related to g_mf by Ladenburg's equation

$$g_nA = 0.667 \times 10^{16}\, g_m f/\lambda^2 \text{ sec}^{-1},$$

where g_n is $(2J+1)$ for the upper level, A is Einstein's transition probability of spontaneous emission, g_m is $(2J+1)$ for the lower level, and f is the absorption oscillator strength.

4. Accuracy of Results

No extensive intensity measurements have been reported heretofore for these lines. Allen and Asaad [8] have reported *gf*-values measured in a 3-amp copper arc and adjusted to an absolute scale, for 135 lines, of which about 80 are found in our list. A comparison of the two sets of values shows a systematic difference which is a function of E and reproduces our normalization function C. This discrepancy arises from the fact that Allen and Asaad used a constant normalization factor. The discrepancy is particularly severe because most of the lines originate above 50 kK, where the value of C is changing rapidly. If this discrepant factor is removed, there is a remaining constant difference; the Allen and Asaad log *gf* is 0.5 less than ours.

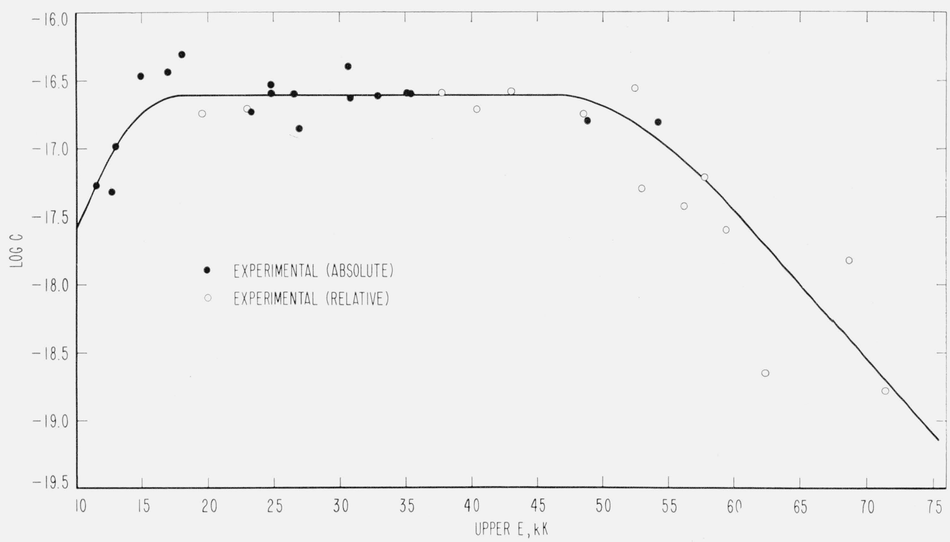

FIGURE 3. *Normalization function for establishing an absolute scale and correcting for departure from thermodynamical equilibrium at high energy levels.*

TABLE 1. *Transition probabilities of copper*

Intensity	Wavelength A	Energy Levels K	gA 10^8/sec	gf	Log gf
78	2626.68	40944 – 79003	0.042	0.0043	−2.36
131	2630.00	39019 – 77031	0.070	0.0073	−2.14
145	2634.93	39019 – 76959	0.078	0.0081	−2.09
41	2645.30	40114 – 77905	0.022	0.0023	−2.63
60	2649.84	40114 – 77841	0.033	0.0034	−2.47
15	2846.48	40944 – 76064	0.0087	0.0011	−2.98
139	2858.22	39019 – 73995	0.080	0.0097	−2.01
185	2858.73	11203 – 46173	0.010	0.0013	−2.89
65	2890.84	44406 – 78988	0.038	0.0048	−2.32
56	2891.64	44544 – 79116	0.033	0.0042	−2.38
11	2931.70	40944 – 75044	0.0065	0.00084	−3.08
29	2933.06	39019 – 73103	0.017	0.0022	−2.66
119	2978.30	43514 – 77080	0.072	0.0096	−2.02
103	2979.38	43514 – 77068	0.063	0.0083	−2.08
98	2998.38	11203 – 44544	0.0036	0.00048	−3.32
161	3012.00	40114 – 73305	0.096	0.013	−1.88
54	3014.85	41153 – 74313	0.033	0.0045	−2.35
191	3021.54	40909 – 73995	0.12	0.016	−1.80
179	3022.61	39019 – 72093	0.11	0.015	−1.84
90	3024.99	30535 – 63585	0.044	0.0060	−2.22
43	3030.26	40114 – 73105	0.026	0.0036	−2.45
37	3044.03	41153 – 73995	0.023	0.0031	−2.50
33	3047.80	30784 – 63585	0.016	0.0022	−2.65
17	3052.55	41563 – 74313	0.010	0.0015	−2.84
13	3053.38	42302 – 75044	0.0080	0.0011	−2.95
27	3068.91	13245 – 45821	0.0014	0.00020	−3.69
980	3073.80	11203 – 43726	0.029	0.0041	−2.39
141	3088.13	40944 – 73316	0.087	0.012	−1.91
838	3099.93	39019 – 71268	0.50	0.073	−1.14
78	3113.48	39019 – 71128	0.047	0.0068	−2.17
78	3120.44	40114 – 72151	0.048	0.0070	−2.16
1294	3126.11	39019 – 70998	0.78	0.11	−0.94
461	3128.70	40114 – 72067	0.28	0.041	−1.38
302	3140.31	39019 – 70853	0.18	0.027	−1.57
638	3142.44	40114 – 71927	0.39	0.058	−1.24
358	3146.82	40114 – 71883	0.22	0.033	−1.49
19	3148.33	41563 – 73316	0.012	0.0018	−2.75
44	3149.51	41563 – 73305	0.028	0.0041	−2.39
286	3156.63	13245 – 44916	0.012	0.0018	−2.74
47	3160.05	41563 – 73199	0.029	0.0044	−2.35
378	3169.68	41563 – 73103	0.24	0.036	−1.45
22	3171.66	44544 – 76064	0.014	0.0021	−2.67
214	3223.44	42302 – 73316	0.14	0.021	−1.67
266	3224.66	42302 – 73305	0.17	0.027	−1.58
501	3231.18	41153 – 72093	0.32	0.050	−1.30
164	3233.90	41153 – 72067	0.10	0.016	−1.79
700	3235.71	42302 – 73199	0.45	0.071	−1.15
1538	3243.16	41153 – 71979	0.98	0.15	−0.81
434	3268.28	41563 – 72151	0.28	0.045	−1.35
1114	3282.72	41563 – 72017	0.72	0.12	−0.94

TABLE 1. *Transition probabilities of copper*—Continued

Intensity	Wavelength A	Energy Levels K	gA 10^8/sec	gf	Log gf
1514	3290.54	40909 – 71291	0.97	0.16	−0.80
116	3292.39	41563 – 71927	0.075	0.012	−1.92
557	3292.83	11203 – 41563	0.0096	0.0016	−2.81
746	3317.22	41153 – 71291	0.48	0.079	−1.10
483	3319.68	41153 – 71268	0.31	0.051	−1.29
206	3329.64	41153 – 71178	0.13	0.022	−1.66
213	3335.22	41153 – 71128	0.14	0.023	−1.64
348	3349.28	42302 – 72151	0.23	0.038	−1.41
703	3365.34	41153 – 70860	0.46	0.077	−1.11
68	3375.67	41563 – 71178	0.044	0.0076	−2.12
308	3381.42	41563 – 71128	0.20	0.035	−1.46
20	3392.02	43726 – 73199	0.013	0.0023	−2.63
37	3396.32	41563 – 70998	0.024	0.0042	−2.38
118	3413.34	45821 – 75109	0.081	0.014	−1.85
177	3440.51	13245 – 42302	0.0039	0.00070	−3.16
531	3457.85	11203 – 40114	0.0064	0.0011	−2.94
49	3459.43	44406 – 73305	0.034	0.0061	−2.22
115	3472.14	44406 – 73199	0.079	0.014	−1.84
22	3474.58	44544 – 73316	0.015	0.0028	−2.56
510	3476.00	44544 – 73305	0.35	0.064	−1.19
750	3483.76	44406 – 73103	0.52	0.094	−1.03
81	3488.86	44544 – 73199	0.056	0.010	−1.99
95	3498.06	43514 – 72093	0.065	0.012	−1.92
71	3500.32	44544 – 73105	0.049	0.0091	−2.04
36	3507.41	43514 – 72017	0.025	0.0046	−2.34
564	3512.12	43514 – 71979	0.39	0.072	−1.14
92	3517.04	43726 – 72151	0.063	0.012	−1.93
367	3520.03	44916 – 73316	0.26	0.048	−1.32
796	3524.23	43726 – 72093	0.55	0.10	−0.99
371	3527.48	43726 – 72067	0.26	0.048	−1.32
1897	3530.38	13245 – 41563	0.035	0.0065	−2.18
360	3533.75	43726 – 72017	0.25	0.047	−1.33
130	3544.96	43726 – 71927	0.090	0.017	−1.77
40	3546.43	44916 – 73105	0.028	0.0053	−2.27
71	3594.02	11203 – 39019	0.00065	0.00013	−3.90
115	3609.30	13245 – 40944	0.0018	0.00036	−3.45
141	3610.81	44406 – 72093	0.100	0.020	−1.71
441	3613.76	43514 – 71178	0.31	0.060	−1.22
168	3614.22	44406 – 72067	0.12	0.023	−1.63
160	3620.35	43514 – 71128	0.11	0.022	−1.66
364	3621.24	44544 – 72151	0.26	0.051	−1.29
30	3629.77	43726 – 71268	0.021	0.0042	−2.38
192	3635.92	45821 – 73316	0.14	0.028	−1.56
105	3641.69	43726 – 71178	0.074	0.015	−1.83
132	3645.23	45879 – 73305	0.096	0.019	−1.72
92	3648.38	43726 – 71128	0.065	0.013	−1.89
312	3655.86	43514 – 70860	0.22	0.044	−1.36
113	3656.78	44544 – 71883	0.081	0.016	−1.79
110	3659.35	45879 – 73199	0.080	0.016	−1.79
26	3664.08	45821 – 73105	0.019	0.0038	−2.42

TABLE 1. *Transition probabilities of copper*—Continued

Intensity	Wavelength A	Energy Levels K	gA 10^8/sec	gf	Log gf
88	3665.74	43726 – 70998	0.062	0.013	−1.90
89	3671.95	45879 – 73105	0.065	0.013	−1.88
32	3695.36	44963 – 72017	0.023	0.0047	−2.32
32	3699.10	46173 – 73199	0.024	0.0048	−2.32
173	3700.54	44963 – 71979	0.13	0.026	−1.59
62	3712.01	46173 – 73105	0.046	0.0094	−2.03
88	3720.77	13245 – 40114	0.0011	0.00024	−3.63
27	3721.67	44406 – 71268	0.019	0.0040	−2.39
120	3734.18	44406 – 71178	0.087	0.018	−1.74
214	3741.24	44406 – 71128	0.15	0.033	−1.49
84	3759.49	44406 – 70998	0.061	0.013	−1.89
100	3771.90	46598 – 73103	0.075	0.016	−1.80
35	3799.88	44544 – 70853	0.026	0.0055	−2.26
71	3800.50	44963 – 71268	0.052	0.011	−1.95
100	3805.23	45879 – 72151	0.075	0.016	−1.79
32	3813.54	44963 – 71178	0.024	0.0052	−2.29
83	3820.88	44963 – 71128	0.061	0.013	−1.87
16	3837.98	45879 – 71927	0.012	0.0027	−2.58
342	3860.47	44963 – 70860	0.25	0.057	−1.25
22	3881.71	46173 – 71927	0.017	0.0038	−2.42
44	3921.27	46598 – 72093	0.034	0.0078	−2.11
52	3925.27	46598 – 72067	0.040	0.0092	−2.03
27	3933.03	46598 – 72017	0.021	0.0048	−2.32
16	3946.94	46598 – 71927	0.012	0.0029	−2.54
7	3951.62	45879 – 71178	0.0054	0.0013	−2.90
11	3979.95	45879 – 70998	0.0084	0.0020	−2.70
5	3993.69	45821 – 70853	0.0038	0.00092	−3.04
10	3998.02	46173 – 71178	0.0077	0.0019	−2.73
53	4003.03	45879 – 70853	0.041	0.0098	−2.01
52	4027.03	46173 – 70998	0.040	0.0098	−2.01
49	4050.62	46173 – 70853	0.038	0.0094	−2.03
52	4052.38	46598 – 71268	0.041	0.010	−2.00
141	4075.57	46598 – 71128	0.11	0.028	−1.56
85	4104.22	40114 – 64472	0.058	0.015	−1.84
37	4121.74	46598 – 70853	0.029	0.0075	−2.13
176	4177.76	39019 – 62948	0.12	0.030	−1.52
432	4248.96	40944 – 64472	0.30	0.082	−1.08
101	4259.40	40114 – 63585	0.069	0.019	−1.73
462	4378.20	40114 – 62948	0.32	0.091	−1.04
92	4415.54	40944 – 63585	0.065	0.019	−1.72
589	4480.35	30535 – 52849	0.19	0.057	−1.24
640	4509.37	42302 – 64472	0.48	0.15	−0.84
263	4539.70	41563 – 63585	0.19	0.059	−1.23
603	4586.97	41153 – 62948	0.43	0.14	−0.86
205	4674.72	41563 – 62948	0.15	0.049	−1.31
84	4697.49	42302 – 63585	0.063	0.021	−1.68
753	4704.59	41153 – 62403	0.54	0.18	−0.74
39	4797.04	41563 – 62403	0.029	0.0099	−2.01
268	5016.61	44544 – 64472	0.22	0.084	−1.08
58	5034.36	43726 – 63585	0.047	0.018	−1.75

TABLE 1. *Transition probabilities of copper*—Continued

Intensity	Wavelength A	Energy Levels K	gA 10^8/sec	gf	Log gf
162	5111.91	44916 – 64472	0.14	0.054	−1.27
138	5144.12	43514 – 62948	0.11	0.044	−1.36
114	5200.87	43726 – 62948	0.093	0.038	−1.42
70	5352.67	43726 – 62403	0.057	0.025	−1.61
30	5354.95	44916 – 63585	0.026	0.011	−1.96
43	5360.03	45821 – 64472	0.038	0.016	−1.78
11	5376.87	45879 – 64472	0.0098	0.0042	−2.37
67	5391.62	44406 – 62948	0.057	0.025	−1.61
38	5432.05	44544 – 62948	0.032	0.014	−1.84
28	5463.14	46173 – 64472	0.025	0.011	−1.95
49	5554.94	44406 – 62403	0.042	0.019	−1.71
40	5732.33	44963 – 62403	0.035	0.017	−1.76
14	6223.66	56030 – 72093	0.017	0.0099	−2.00
12	6325.45	46598 – 62403	0.012	0.0070	−2.16
18	6474.20	56651 – 72093	0.023	0.014	−1.84
12	6485.18	56651 – 72067	0.015	0.0096	−2.02
3.0	6506.14	56651 – 72017	0.0038	0.0024	−2.61
4.7	6544.51	56651 – 71927	0.0060	0.0039	−2.41
4.1	6550.98	56030 – 71291	0.0052	0.0034	−2.47
4.3	6583.54	58119 – 73305	0.0056	0.0037	−2.44
3.4	6599.68	56030 – 71178	0.0043	0.0028	−2.55
30	6621.61	56030 – 71128	0.038	0.025	−1.60
6	6629.67	58119 – 73199	0.0079	0.0052	−2.28
24	6672.23	58119 – 73103	0.032	0.021	−1.67
101	6741.42	56030 – 70860	0.13	0.089	−1.05
8	6881.94	56651 – 71178	0.011	0.0076	−2.12
8	6890.90	57419 – 71927	0.011	0.0077	−2.11
44	6905.94	56651 – 71128	0.059	0.042	−1.38
3.8	6968.34	56651 – 70998	0.0051	0.0037	−2.43
4.5	7154.29	58119 – 72093	0.0063	0.0048	−2.31

The accuracy of the intensity measurements made in the copper arc is discussed in references [1] and [2]. Comparison of repeated determinations indicates that the standard deviation of an individual determination of the intensity of copper lines is about 2 or 3 percent.

The accuracy of the *gf*-values derived from intensity measurements is discussed in references [4] and [5]. In the case of our copper lines, about 2/3 of them arise from levels between 70 and 80 kK above the ground state. For these lines the standard deviation in log *gf* that arises from the uncertainty in T is about 0.18 (50 percent in *gf*) and the error due to the uncertainty in the intensity (0.01) is negligible. To estimate the absolute error in these high level lines we add again the error due to the uncertainty of T in the Boltzmann factor in Saha's equation (0.18) and the error introduced by the uncertainty in the value of the electron density in Saha's equation (0.17). Adding these as the square root of the sums of the squares we find the standard deviation of an individual determination of the absolute value of log *gf* is 0.3, or about a factor of 2 in *gf*.

The results in table 1 were calculated from the formulas in section 3 by W. R. Bozman using a modification of the program he developed for NBS Mono. 53 [4].

5. References

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